Use of in situ volumetric water content at field capacity to improve prediction of soil water retention properties

Hassan Al Majou[1,2], Ary Bruand[1], Odile Duval[3]

[1] *Université d'Orléans, CNRS, INSU, Université de Tours, - Institut des Sciences de la Terre d'Orléans (ISTO), 1A Rue de la Férollerie, 45071 Orléans Cedex 2, France;* [2] *Université de Damas, Département des Sciences du Sol, Faculté Agronomique, PO Box 30621, Damas, Syrie;* [3] *INRA Orléans, UR0272 de Science du sol, Centre de Recherche d'Orléans, BP20619, 45166 Olivet Cedex, France.*

Al Majou, H., Bruand, A., Duval, O. 2007. **Use of in situ volumetric water content at field capacity to improve prediction of soil water retention properties.** Most pedotransfer functions (PTFs) developed over the last three decades to generate water retention characteristics use soil texture, bulk density and organic carbon content as predictors. Despite of the high number of PTFs published, most being class- or continuous-PTFs, accuracy of prediction remains limited. In this study, we compared the performance of different class- and continuous-PTFs developed with a regional database. Results showed that use of in situ volumetric water content at field capacity as a predictor led to much better estimation of water retention properties as compared to using predictors derived from the texture, or the organic carbon content and bulk density. This was true regardless of the complexity of the PTFs developed. Results also showed that the best prediction quality was achieved by using the in situ volumetric water content at field capacity after stratification by texture. Comparison of in situ volumetric water content at field capacity, with the water retained at different matric potentials as measured in the laboratory, showed field capacity to approximate 100 hPa whatever the soil texture. Finally, the lack accuracy of PTFs that do not use the in situ volumetric water content at field capacity as predictor did not appear due to the test soils being unrepresentative of the soils used to develop the PTFs, but were instead related to poor correlations between the predictors used and the water retention properties.

Key words: Pedotransfer functions, RMSE, MEP, SDP, texture, bulk density, organic carbon content,

Al Majou, H., Bruand, A., Duval, O. 2007. **Utilisation de la teneur en eau volumique à la capacité au champ in situ pour améliorer la prédiction des propriétés de rétention en eau des sols.** La plupart des fonctions de pédotransfert (FPT) développées durant les trois dernières décennies pour prédire les propriétés de rétention en eau des sols ont utilisé des caractéristiques dérivées de la composition granulométrique, la teneur en carbone organique et la densité apparente comme prédicteurs. En dépit du nombre élevé de FPT publiées qui sont le plus souvent des classes de fonctions de pédotransfert ou des fonctions de pédotransfert continues, la précision des prédictions reste faible. Dans cette étude, nous avons comparé les performances de différentes FPT développées à partir d'une base de données régionale. Les résultats montrent que l'utilisation de la teneur en eau volumique à la capacité au champ in situ comme prédicteur conduit à des prédictions de qualité supérieure à celles enregistrées avec des prédicteurs dérivés de la composition granulométrique, ou avec la teneur en carbone organique et la densité apparente quelle que soit la complexité des FPT développées. Les résultats montrent aussi que la meilleure prédiction est enregistrée en utilisant la teneur en eau volumique à la capacité au champ in situ après stratification en fonction de la texture. La comparaison de la teneur en eau volumique à la capacité au champ avec celle enregistrée aux différents potentiels matriciels montre que celle-ci est proche de la teneur en eau à 100 hPa quelle que soit la texture. Ainsi, parce qu'elle peut être considérée comme l'approximation d'un point de la courbe de rétention en eau à une valeur particulière de potentiel, la teneur en eau volumique à la capacité au champ est le meilleur prédicteur de l'ensemble de la courbe de rétention en eau. Enfin, si l'on met de coté les FPT développées avec la teneur en eau volumique à la capacité au champ, les résultats montrent une faible précision des prédictions enregistrées avec les classes de FPT et les FPT continues étudiées bien que le jeu de données de test ait des caractéristiques moyennes proches de celles du jeu de données utilisé pour établir les FPT étudiées. La faible précision des FPT étudiées ne serait pas liée, comme souvent évoqué dans la littérature, à une faible représentativité des sols utilisés pour développer les FPT mais à la faiblesse de la relation entre les prédicteurs utilisés et les propriétés de rétention en eau.

Mots clés: Fonctions de pédotransfert, EQM, EMP, ETP, texture, densité apparente, teneur en carbone organique

Abbreviations: **PTFs,** pedotransfer functions; **WRC,** water retention characteristics; **OC,** organic carbon; **FC,** field capacity; **CEC**, cation exchange capacity; **RMSE**, root mean square error; **MEP**, mean error of prediction; **SDP**, standard deviation of prediction

INTRODUCTION

Soil hydraulic properties are required for models that simulate water and chemical transport in soils. With the increased application of these models, there is a growing demand for soil hydraulic property data. However, such data are scarce because of the extensive time and costs associated with measurement. A common solution to this problem is to use pedotransfer functions (PTFs) that relate more readily accessed soil properties to the harder to obtain properties such as the water retention characteristic and the hydraulic conductivity function (Bouma and van Lanen, 1987; Bouma, 1989; van Genuchten and Leij, 1992). Many PTFs were developed to predict water retention characteristics over the last three decades, most being continuous-pedotransfer functions (continuous-PTFs) that are mathematical functions relating basic soil properties (e.g. particle size distribution, organic carbon content, dray bulk density) to volumetric water content at discrete soil water matric potentials, or to water retention curve parameters (Bastet *et al.*, 1999; Wösten *et al*., 2001; Nemes *et al*., 2003; Nemes and Rawls, 2004; Pachepsky *et al*., 2006). Besides these continuous-PTFs that enable estimation of volumetric water content at any matric potentials (e.g. Rawls *et al*., 1982; Hall *et al*., 1977; Gupta and Larson, 1979; Rawls *et al*. 1991) or estimation of the water retention curve parameters (Vereecken *et al*., 1989; Minasny *et al*. 1999; Lilly et al., 1999; Wösten *et al*. 1995; Cresswell et al., 2006), there are also class pedotransfer functions (class-PTFs) that provide average water contents at particular water potentials or one average water retention curve for every texture class (Nemes *et* al., 2001; Nemes, 2002; Bruand *et al*., 2003; Al Majou et al., 2007).

Whatever the type of PTF, Wösten et al. (2001) showed a large range of accuracy with the root mean square error (*RMSE*) of predicted volumetric water contents ranging from 0.02 to 0.11 $m^3 m^{-3}$. The smallest *RMSE* of 0.02 $m^3 m^{-3}$ was recorded in studies where small data set of soils were analysed or one or more measured points of the water retention curve were used. In the other studies reviewed by Wösten et al. (2001), the *RMSE* recorded was $\geq 0.04 m^3 m^{-3}$. Use of one or two measured points of the water retention curve such as in the work of Rawls et al. (1982) and Paydar and Cresswell (1996) is somewhat in contradiction with the utilization of PTFs to predict the entire water retention curve. PTFs should indeed enable prediction of the water retention curve avoiding measurement of particular points of that curve. However, as shown by Wösten et al. (2001), points on the water retention curve considerably improve prediction of water retention. In this study, the objective is to show that use of the in situ volumetric water content at field capacity can substantially improve PTF predictions of water retention properties without measuring points on water retention curve.

Thus, without measurement of one or more points of the water retention curve, it is possible to gain advantage of the increase in the prediction quality when points of that curve are used as predictors.

MATERIALS AND METHODS

The soils studied

Pedotransfer functions were developed by using a set of 320 horizons comprising 90 topsoil horizons (from 0 to 30 cm depth) and 230 subsoil horizons (> 30 cm depth) collected in Cambisols, Luvisols, Planosols, Albeluvisols, Podzols and Fluvisols (ISSS Working Group R.B., 1998) located mainly in the Paris basin. The horizon bulk density (D_b in Mg m^{-3}) was measured by using cylinders 1236 cm^3 in volume (Ø = 15 cm; H = 7 cm) when the soil was at field capacity, namely in winter two to three days after a period of several days of rainfall (Bruand and Tessier, 2000). The water content at field capacity was measured on the soil material collected with the cylinders for bulk density determination. The particle size distribution was measured using the pipette method after pre-treatment of samples with hydrogen peroxide and sodium hexametaphosphate (Robert & Tessier 1974). The cation exchange capacity (CEC, in cmol kg^{-1} of oven-dried soil) was measured using the cobalt-hexamine trichloride method (Ciesielski & Sterckeman 1997) and organic carbon content (*OC*) by oxidation using excess potassium bichromate in sulphuric acid at 135°C (Baize 2000). Volumetric water content was determined using the pressure plate extractor method at 10 hPa (θ_{10}), 33 hPa (θ_{33}), 100 hPa (θ_{100}), 330 hPa (θ_{330}), 1000 hPa (θ_{1000}), 3300 hPa (θ_{3300}) and 15000 hPa (θ_{15000}) matric potential by using undisturbed samples (30-70 cm^3 in volume) collected when the soil at field capacity (Bruand and Tessier, 2000). A set of 133 horizons was assembled in order to verify the PTFs established. These horizons were collected in

Cambisols, Luvisols, Planosols, Albeluvisols and Podzols (ISSS Working Group R.B., 1998) distributed throughout the whole of France. The basic properties and water retention properties of these 133 test horizons were determined using the same methods as were used to develop the PTFs studied.

Analysis of the PTF performance

To verify the PTF, the root mean square error (*RMSE*) was computed using:

$$RMSE = \left\{ \frac{1}{l' \cdot l} \sum_{j=1}^{l'} \sum_{i=1}^{l} \left(\theta_{p,j,i} - \theta_{m,j,i} \right)^2 \right\}^{1/2} \quad (1)$$

where $\theta_{p,j,i}$ is the predicted water content at potential *i* for the horizon *j*, $\theta_{m,i,j}$ is the measured water content at matric potential *i* for the horizon *j*, and *l* is the number of matric potential for each horizon (*l*=7 in this study) and *l'* is the number of horizons ($l' \leq 133$ in this study). Although *RMSE* is commonly used to test PTFs (e.g. Wösten *et al.*, 2001; Schaap, 2004), it varies according to both the overall prediction bias and the overall prediction precision. To determine the prediction bias and prediction precision, separately, we computed the mean error of prediction (*MEP*) and the standard deviation of prediction (*SDP*) using (Bruand et al., 2003):

$$MEP = \frac{1}{l' \cdot l} \sum_{j=1}^{l'} \sum_{i=1}^{l} (\theta_{p,j,i} - \theta_{m,j,i}) \quad (2)$$

$$SDP = \left\{ \frac{1}{l' \cdot l} \sum_{j=1}^{l'} \sum_{i=1}^{l} \left[(\theta_{p,j,i} - \theta_{m,j,i}) - MEP \right]^2 \right\}^{1/2} \quad (3)$$

The *MEP* indicates whether the PTFs overestimated (positive) or underestimated (negative) the water content, on average, whereas *SDP* measures the precision of the prediction.

RESULTS AND DISCUSSION

Characteristics of the soils studied

The mean basic properties of the horizons of the test data set were close to those of the horizons used to develop the PTFs (Fig 1, Table 1). The test data set showed however a higher mean clay, sand and organic carbon content. The variability attached to the mean silt and sand content, as well as to the CEC was greater in the test data set. It was the opposite for the $CaCO_3$ content. Results also showed similar mean θ at every pressure head except for θ_{15000} which was greater in the test dataset (+0.023 m^3 m^{-3}) than in the data set used to establish the PTFs. That greater mean θ_{15000} would be related to the smaller mean $CaCO_3$ content (–27 g kg^{-1}) and greater organic carbon content (+1.1 g kg^{-1}) in the test data set and secondarily to the slightly greater clay content (+1.3 wt. %) in the test data set.

The class-PTFs developed

Class-PTFs corresponding to the average θ at the 7 matric potentials were developed according to the texture alone (texture class-PTFs) in the FAO triangle (FAO, 1990) (Figure 1a and Table 2). Class-PTFs were also established by fitting the van Genuchten's model (1980) on the arithmetic mean value of θ at the different water potentials by using the RETC code (van Genuchten *et al.*, 1991) for every class of texture (VG class-PTFs) in the FAO triangle (FAO, 1990) and according to the type of horizon (topsoil and subsoil) as done previously by Wösten et al. (1999) (Table 3). The residual water content was fixed at 0.010 cm cm^{-3} except for texture Coarse for which it was fixed at 0.025 cm cm^{-3} as earlier done by Wösten et al. (1999). The parameter m was computed as $m = 1 - 1/n$. A water content approximating the water content at saturation was computed using the porosity deduced from D_b (particle density equalled to 2.65 Mg m^{-3}) and added to the seven values of measured volumetric water content. The RETC code was then run by fixing arbitrarily the matric potentials at 1 hPa for the saturated volumetric water content.

The continuous-PTFs developed

Following the early works of Gupta and Larson (1979) and Rawls et al. (1982), continuous-PTFs were developed by multiple regression equations (RG continuous-PTFs) as follows:

$$\theta_h = a + (b\times Cl) + (c\times Si) + (d\times OC) + (e\times D_b) \quad (4)$$

where θ_h is the volumetric water content (m^{3}m^{-3}) at matric potential h, Cl and Si are respectively the clay and silt content as wt. %, and *a, b, c, d, and e* are regression coefficients (Table 4). Continuous-PTFs were also established by simple regression by using the volumetric water content measured when the soil was at field capacity (θ_{FC}), namely in winter two to three days after a period of several days of rainfall, as predictor without any texture stratification (FC continuous-PTFs) as follows:

$$\theta_h = a' + b'\times\theta_{FC} \quad (5)$$

where θ_{FC} is the volumetric water content (m^{3}m^{-3}) at field capacity, a' and b' are regression coefficients (Table 5). Similar continuous-PTFs were developed with θ_{FC} as predictor after stratification by texture (FC-textural continuous-PTFs) (Table 5). Finally, continuous-PTFs were developed for the parameters of the van Genuchten's model using multiple regression equations (VG continuous-PTFs) as done previously by Wösten *et al*. (1999) (Table 6). Prior to the development of PTFs, the parameters of the van Genuchten's model were computed by using the RETC code (van Genuchten *et al.*, 1991) for every horizon as performed for the VG class-PTFs (Table 6).

PTFs verification

The *RMSE* recorded for the different class-PTFs studied was 0.045 $m^3 m^{-3}$ (Fig 2a, b). Similar values were reported by Wösten et al. (2001). This high *RMSE* was related to a relatively poor prediction precision when the prediction bias was very small. The absolute value of $|MEP|$ ($0.001 \leq MEP \leq 0.002$ $m^3 m^{-3}$) was indeed much smaller than *SDP* (0.045 $m^3 m^{-3}$). The very small bias recorded with class-PTFs can be related to the similarity between the characteristics of the soils used to establish the PTFs and those used to test them as indicated by the average basic soil properties and water contents of the two sets of soils (Table 1). In spite of this similarity between the two data sets, high *SDP* was recorded thus indicating that the poor performance of the class-PTFs studied did not indicate a small representativeness of the data set used to develop PTFs as is often suggested (Bastet et al., 1999; Wösten et al., 2001). On the contrary, this would indicate the lack of ability of the PTFs studied to take into account the sources of variability for the water retention properties for the soils studied.

On the other hand, the *RMSE* recorded with the continuous-PTFs was smaller ($0.027 \leq RMSE \leq 0.040$ $m^3 m^{-3}$) than with the class-PTFs (Fig 2c, d, e, f). A small *RMSE* was already recorded with the *FC* continuous-PTFs (*RMSE* = 0.032 $m^3 m^{-3}$) (Fig 2c), but the smallest *RMSE* was recorded with the texture-*FC* continuous-PTFs (*RMSE* = 0.027 $m^3 m^{-3}$) (Fig 2d), thus indicating that combining texture and field capacity improved the prediction of water retention properties. This improvement in the prediction was related to an increase in the prediction precision (*SDP* = 0.026 and 0.031 $m^3 m^{-3}$ with the Texture-*FC* and *FC* continuous-PTFs respectively), the prediction bias remaining very small as recorded with the class-PTFs.

Thus, if we exclude *FC* and Texture-*FC* continuous-PTFs, we note that a *RMSE* close to, and greater than, 0.040 $m^3 m^{-3}$ was recorded with the class- and continuous-PTFs discussed in this study. Such high *RMSE* were often related in the literature to the difference existing between the soils of the data set used to develop PTFs and those of the test data set (Wösten et al., 2001). In our study, the soils of the two data sets showed close mean basic characteristics but nevertheless the different PTFs discussed led to high *RMSE* (Fig 2), thus indicating that the PTFs studied that did use the in situ water content at field capacity were intrinsically inaccurate.

In situ field capacity and matric potential

The mean difference (*MD*) between θ_{FC} and successively θ_{33}, θ_{100} and θ_{330} was computed as follows:

$$MD = \frac{1}{l'}\sum_{j=1}^{l'}(\theta_{FC,j} - \theta_{m,j,i}) \quad (6)$$

where $\theta_{FC,j}$, is the volumetric water content (m^3 m^{-3}) at field capacity of the horizon *j*, $\theta_{m,i,j}$ is the measured water content at matric potential *i* for the horizon *j*, and *l'* is the number of horizons (*l'* = 133 in this study). The smallest *MD* was recorded with θ_{100} (*MD* = 0.005 m^3 m^{-3}) and there was small variation according to the texture (Fig 3). The smallest *MD* was recorded for Medium, Medium Fine and Fine texture (*MD* = 0.002 m^3 m^{-3}) and the greatest MD for Coarse texture (*MD* = 0.022 m^3 m^{-3}).

As shown by Rawls et al. (1982) and Paydar and Cresswell (1996) use of one or more measured points on the water retention curve enable improved prediction of the whole curve when compared to its prediction with the texture, organic matter content and bulk density. Here, we showed that θ_{FC}, and particularly when combined with texture, enabled improved prediction of the water retention curve compared to estimation with usual predictors. The efficiency of θ_{FC} as predictor is related to the fact that it can be considered as a water content corresponding to a narrow range of matric potential, as shown by the very small MD when compared to θ_{100}.

CONCLUSION

Results showed that use of the in situ volumetric water content at field capacity as a predictor led to much better estimation of water retention properties as compared to using predictors derived from the texture, or with the organic carbon content and bulk density. This was true regardless of the complexity of the PTFs developed. Results also showed that the most accurate prediction was gained through using the in situ volumetric water content at field capacity after stratification by texture according to the FAO triangle. Comparison of the in situ volumetric water content at field capacity with the water retained at the different matric potentials showed that it was close to the water content at 100 hPa matric potential whatever the texture. Thus, because it can be considered as a point of the water retention curve at a particular matric potential, the field capacity was the best predictor of the entire water retention curve. Thus, it appears possible to predict the water retention properties more accurately with the in situ volumetric water content at field capacity than with more sophisticated data such as those derived from the particle size distribution, organic carbon content or bulk density. Finally, results showed poor accuracy of the class- and continuous-PTFs studied, except for the PTFs developed with the volumetric water content at field capacity, although the test data set had average characteristics close to those of the soils used to develop the PTFs. The poor accuracy of the PTFs were not mainly related to a poor representativeness of the soils used to develop the PTFs, but to a poor correlation between the usual predictors used (i.e. texture, organic carbon content, dry bulk density) and the soils water retention properties.

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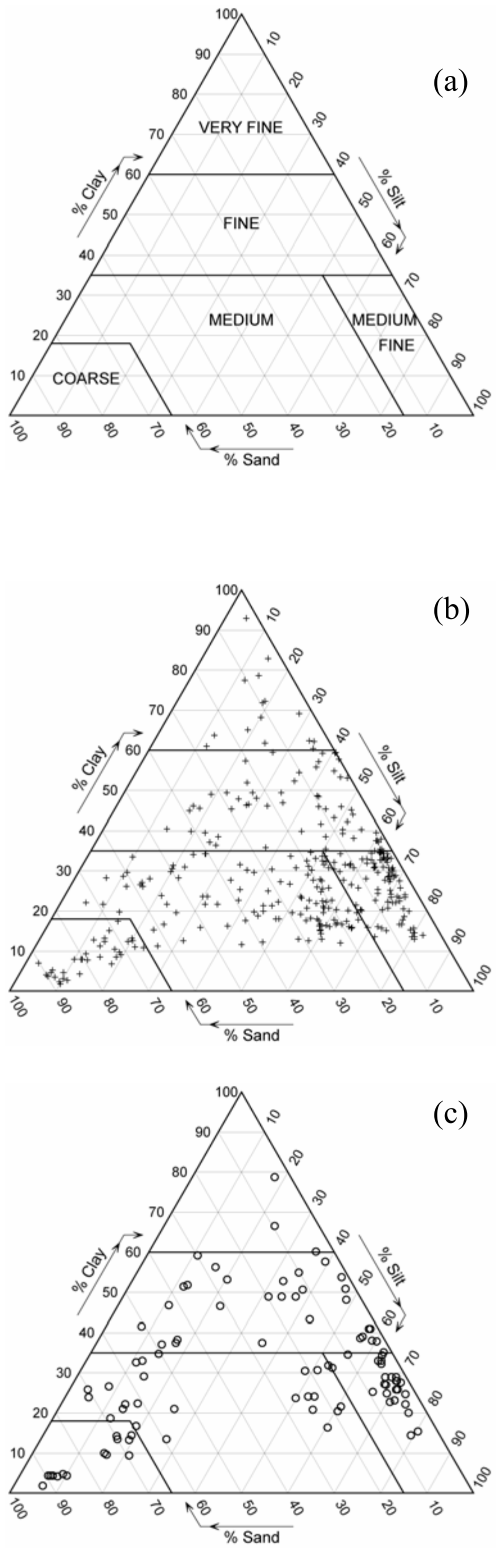

Fig 1. Triangle of texture used (FAO, 1990) (a), texture of the horizons used to establish the class pedotransfer functions (PTFs) (b) and those used for their verification (c).

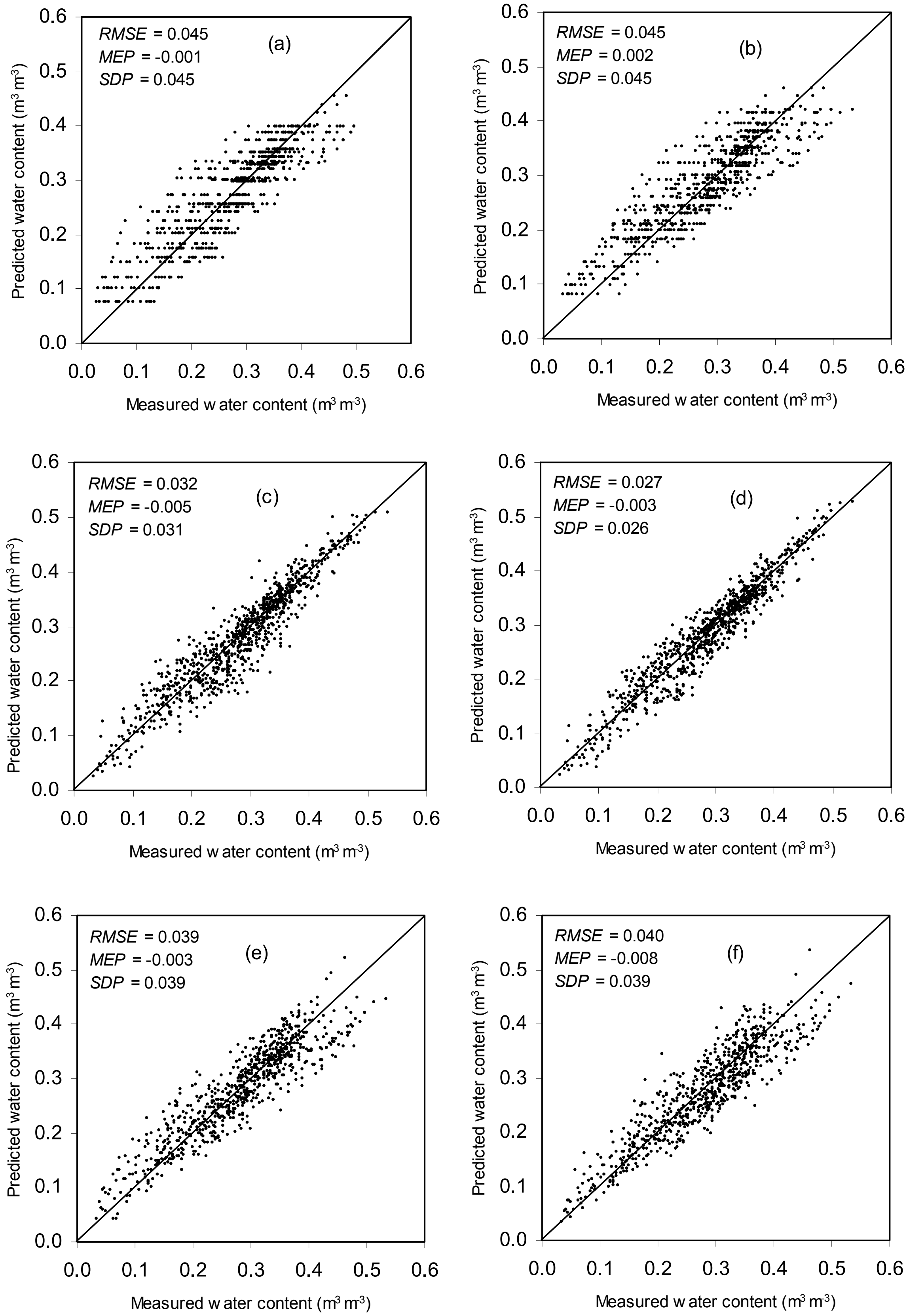

Fig 2. Comparison of measured and predicted volumetric water content on prediction set using (a) texture alone, (b) VG class-PTFs, (c) FC continuous-PTFs, (d) FC-textural continuous-PTFs, (e) RG continuous-PTFs and, (f) VG continuous-PTFs (RMSE: root mean square error; MEP: mean error of prediction; SDP: standard deviation of prediction).

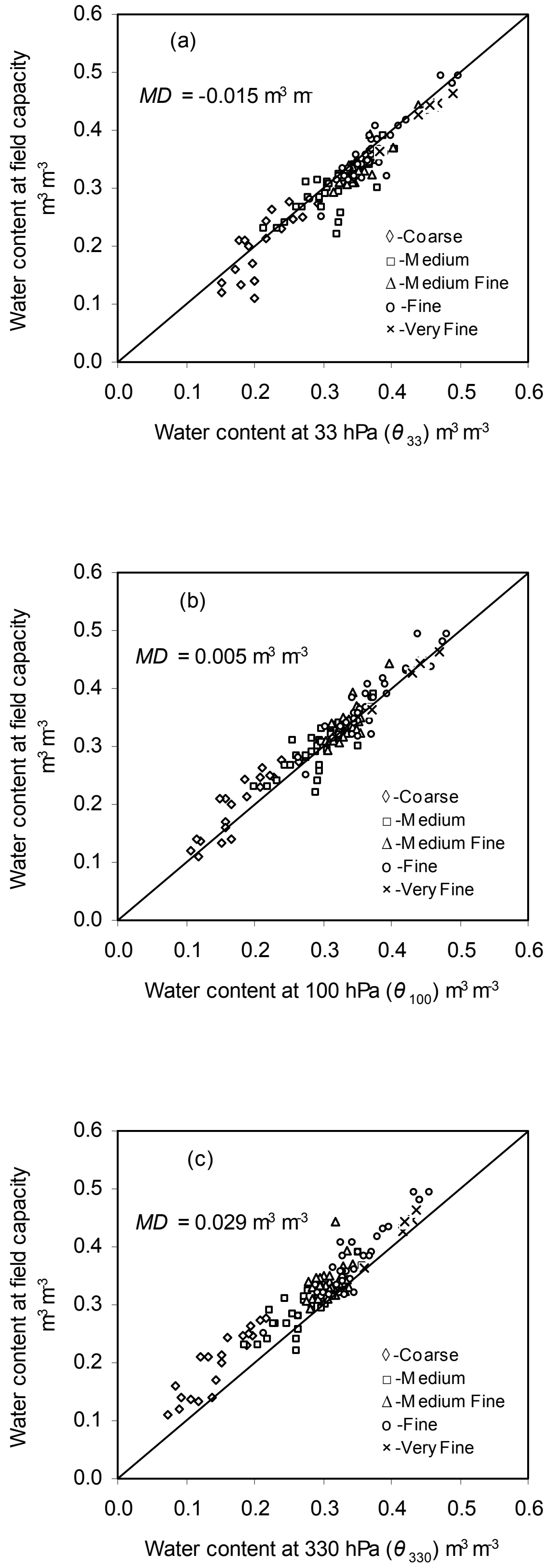

Fig 3. The mean difference (*MD*) between the volumetric water content at field capacity (θ_{FC}) and successively θ_{33} (a), θ_{100} (b) and θ_{330} (c) and according to the texture class.

Table 1. Characteristics of the horizons of the soil database used to develop the PTFs studied and of the data set used to test them.

	Particle size distribution (wt. %)			*OC* g kg^{-1}	$CaCO_3$ g kg^{-1}	*CEC* cmol$_c$kg^{-1}	D_b Mg m^{-3}	Volumetric water content (m^3 m^{-3}) at matric potential h (θ_h)						
	<2 µm	2-50 µm	50-2000 µm					θ_{10}	θ_{33}	θ_{100}	θ_{330}	θ_{1000}	θ_{3300}	θ_{15000}
Data set used to develop the PTFs (n = 320)														
mean	28.9	46.2	24.9	5.7	65	14.3	1.53	0.350	0.335	0.316	0.289	0.257	0.220	0.179
s.d.	15.1	20.8	23.9	4.9	189	8.0	0.15	0.067	0.065	0.070	0.070	0.075	0.074	0.070
min.	1.9	2.8	0.1	0.0	0.0	0.8	1.00	0.123	0.100	0.080	0.056	0.048	0.033	0.013
max.	92.9	82.1	90.1	28.8	982	52.8	1.84	0.606	0.596	0.586	0.558	0.510	0.462	0.370
Data set used to test the PTFs developed (n = 133)														
mean	30.2	40.6	29.2	6.6	38	15.8	1.51	0.356	0.332	0.312	0.287	0.261	0.224	0.202
s.d.	15.4	24.3	28.6	5.3	134	10.8	0.13	0.075	0.079	0.082	0.084	0.086	0.083	0.080
min.	1.9	4.1	1.6	0.0	0.0	0.6	1.10	0.161	0.121	0.099	0.072	0.045	0.041	0.033
max.	78.7	80.3	91.8	28.2	656	50.2	1.77	0.534	0.498	0.482	0.457	0.440	0.396	0.369

OC = organic carbon content; $CaCO_3$ = calcium carbonate content; CEC = cation exchange capacity; D_b = bulk density.

Table 2. Water retained ($m^3 m^{-3}$) and standard error (*s.e.*) associated at the different matric potentials (θ_h) after stratification by texture alone (texture class-PTFs).

		Volumetric water content ($m^3 m^{-3}$)) at matric potential h (θ_h)						
		θ_{10}	θ_{33}	θ_{100}	θ_{330}	θ_{1000}	θ_{3300}	θ_{15000}
Very fine (n = 15)	mean	0.455	0.437	0.424	0.402	0.385	0.357	0.322
	s.e.	0.019	0.015	0.014	0.013	0.012	0.010	0.010
Fine (n = 60)	mean	0.399	0.388	0.373	0.351	0.331	0.301	0.254
	s.e.	0.009	0.009	0.009	0.008	0.008	0.007	0.006
Medium fine (n = 96)	mean	0.356	0.342	0.327	0.298	0.254	0.210	0.173
	s.e.	0.002	0.002	0.002	0.002	0.004	0.004	0.004
Medium (n = 117)	mean	0.334	0.320	0.302	0.273	0.242	0.203	0.156
	s.e.	0.004	0.004	0.003	0.003	0.004	0.004	0.004
Coarse (n = 32)	mean	0.249	0.224	0.181	0.149	0.120	0.100	0.076
	s.e.	0.013	0.012	0.012	0.010	0.009	0.008	0.006

Table 3. Parameters of the van Genuchten's model corresponding to the VG textural class-PTFs developed according to the texture and type of horizon (topsoil and subsoil).

	θr	θs	α	n	m
			Topsoils		
Very Fine (n = 15)	0.010	0.587	5.9433	1.0658	0.0617
Fine (n = 60)	0.010	0.477	0.6153	1.0652	0.0612
Medium fine (n = 96)	0.010	0.465	0.6860	1.1027	0.0931
Medium (n = 117)	0.010	0.428	0.4467	1.1000	0.0909
Coarse (n = 32)	0.025	0.397	1.0592	1.1530	0.1327
			Subsoils		
Very Fine (n = 15)	0.010	0.472	0.0745	1.0499	0.0475
Fine (n = 60)	0.010	0.437	0.1334	1.0632	0.0594
Medium fine (n = 96)	0.010	0.416	0.1611	1.0978	0.0891
Medium (n = 117)	0.010	0.388	0.1851	1.0992	0.0903
Coarse (n = 32)	0.025	0.367	1.0535	1.1878	0.1581

Table 4 Regression coefficients *a*, *b*, *c*, *d* and *e*, and coefficient of determination R^2 recorded for the RG continuous-PTFs.

	Pressure head (hPa)						
	10	33	100	330	1000	3300	15000
a	0.4701^{***}	0.3556^{***}	0.2620^{***}	0.1301^{***}	0.0184	-0.0504	-0.0786^{**}
b	0.0026^{***}	0.0029^{***}	0.0034^{***}	0.0038^{***}	0.0045^{***}	0.0047^{***}	0.0045^{***}
c	0.0006^{***}	0.0008^{***}	0.0012^{***}	0.0012^{***}	0.0008^{***}	0.0005^{***}	0.0003^{***}
d	-0.0006	-0.0002	0.0002	0.0010	0.0017^{***}	0.0012^{**}	0.0004
e	-0.1447^{***}	-0.0939^{***}	-0.0647^{***}	-0.0084	0.0398^{*}	0.0697^{***}	0.0710^{***}
R^2	0.59	0.64	0.69	0.74	0.77	0.82	0.86

$\theta_h = a + (b \times Cl) + (c \times Si) + (d \times OC) + (e \times D_b)$ with θ_h volumetric water content at a matric potential h; Cl = clay content (wt. %) ; Si = silt content (wt. %) ; OC = organic carbon content; D_b = bulk density; *** P = 0.001; ** P = 0.01; * P = 0.05.

Table 5. Regression coefficients *a'* and *b'*, and coefficient of determination R^2 recorded for the continuous-PTFs established by simple regression by using θ_{FC} as predictor without stratification by texture (FC continuous-PTFs) and after stratification by texture (FC-textural continuous-PTFs).

		Matric potential (hPa)						
		10	33	100	330	1000	3300	15000
					FC continuous-PTFs			
All textures together	*a'*	0.0745^{***}	0.0385^{***}	-0.0091	-0.0329^{***}	-0.0673^{***}	-0.0611^{***}	-0.0593^{***}
(n = 320)	*b'*	0.8766^{***}	0.9394^{***}	1.0286^{***}	1.0164^{***}	1.0252^{***}	0.8851^{***}	0.7535^{***}
	R^2	0.77	0.86	0.90	0.87	0.79	0.66	0.52
					FC-textural continuous-PTFs			
Very Fine	*a'*	-0.0516	0.0467	0.0584	0.0580	0.0724	0.1946^{***}	0.0801
(n = 15)	*b'*	1.2359^{***}	0.9515^{***}	0.8915^{***}	0.8386^{***}	0.7639^{***}	0.3733^{**}	0.5910^{***}
	R^2	0.87	0.85	0.87	0.85	0.85	0.59	0.69
Fine	*a'*	0.0391	0.0410^{*}	0.0165	0.0304	0.0192	0.0603^{**}	0.1184^{***}
(n = 60)	*b'*	0.9827^{***}	0.9473^{***}	0.9677^{***}	0.8665^{***}	0.8437^{***}	0.6415^{***}	0.3789^{***}
	R^2	0.81	0.86	0.86	0.78	0.79	0.67	0.44
Medium fine	*a'*	0.1769^{***}	0.1472^{***}	0.1525^{***}	0.1493^{***}	0.0561	0.0723	0.0743
(n = 96)	*b'*	0.5475^{***}	0.5959^{***}	0.5323^{***}	0.4557^{***}	0.6083^{***}	0.4208^{*}	0.3035
	R^2	0.26	0.48	0.44	0.25	0.13	0.05	0.03
Medium	*a'*	0.1180^{***}	0.0901^{***}	0.0607^{***}	0.0471^{**}	0.0410^{*}	0.0536^{**}	0.0706^{**}
(n =117)	*b'*	0.7207^{***}	0.7618^{***}	0.7991^{***}	0.7479^{***}	0.6735^{***}	0.5022^{***}	0.2908^{**}
	R^2	0.48	0.60	0.69	0.65	0.55	0.39	0.11
Coarse	*a'*	0.0981^{*}	0.0105	-0.0602^{**}	-0.0573^{**}	-0.0564^{**}	-0.0564^{***}	-0.0445^{**}
(n = 32)	*b'*	0.8080^{***}	1.0867^{***}	1.2318^{***}	1.0587^{***}	0.9020^{***}	0.8011^{***}	0.6108^{***}
	R^2	0.36	0.61	0.85	0.81	0.80	0.80	0.73

$\theta_h = a' + (b' \times \theta_{FC})$ with θ_h volumetric water content ($m^3\ m^{-3}$) at a matric potential h and θ_{FC} volumetric water content ($m^3\ m^{-3}$) at field capacity; *** P = 0.001; ** P = 0.01; * P = 0.05.

Table 6. Continuous-PTFs developed for the parameters of the van Genuchten's model (VG continuous-PTFs).

$\theta_s = 1.1658 - 0.0032*Cl - 0.4737*D_b + 2*10^{-7}*Si^2 - 0.0001*OC^2 + 0.0373*Cl^{-1} + 0.0131*Si^{-1} - 0.0072*\ln(Si) + 0.00003*OC*Cl + 0.0022*D_b*Cl - 0.0002*D_b*OC - 0.0001*Si$
($R^2 = 0.95$)

$\alpha^* = 25.61 + 0.0439*Cl + 0.1129*Si + 1.1914*OC + 32.21*D_b - 10.48*D_b^2 - 0.0009*Cl^2 - 0.0146*OC^2 - 0.3781*OC^{-1} - 0.0178*\ln(Si) - 0.1032*\ln(OC) - 0.1*D_b*S - 0.6001*D_b*OC$
($R^2 = 0.26$)

$n^* = -15.29 - 0.0659*Cl + 0.0115*Si - 0.2115*OC + 12.33*D_b - 1.3578*D_b^2 + 0.0006*Cl^2 + 0.0031*OC^2 + 4.0005*D_b^{-1} + 2.2003*Si^{-1} + 0.1643*OC^{-1} - 0.1205*\ln(Si) + 0.2693*\ln(OC) - 9.9367*\ln(D_b) + 0.003*D_b*Cl + 0.0694*D_b*OC$
($R^2 = 0.35$)

θ_s is a model parameter, α^*, n^* are transformed model parameters in the van Genuchten equations; Cl = wt. % of clay; Si= wt. % of silt; OC = organic carbon ($g.kg^{-1}$); D_b = bulk density ($Mg\ m^{-3}$).